Far-Infrared Spectroscopy of NGC 6946, IC 342, and Arp 299

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ABSTRACT

We have investigated the physical conditions in the infrared bright galaxies NGC 6946, IC 342, and Arp 299 through measurements of far-infrared emission lines from Si II, O I, C II, and O III using the facility Cooled Grating Spectrometer on the Kuiper Airborne Observatory. These data are interpreted using our theoretical models for photodissociation regions and H II regions. For the central 45″ of these galaxies, we have determined that the dominant excitation mechanism for the FIR lines is FUV radiation from young stars, and we have derived the total mass, density, and temperature of the warm atomic gas and the typical sizes, number densities, and filling factors for the interstellar clouds.

I. INTRODUCTION

A determination of the physical parameters in the interstellar medium (ISM) of galactic nuclei requires far-infrared (FIR) line measurements. Observations at other wavelengths cannot adequately probe these heavily-obscured regions: optical lines are often so heavily reddened that large extinction corrections render interpretation difficult; radio continuum observations of the ionized gas are often confused by a large nonthermal component; and millimeter observations of molecular emission probe only the relatively cold gas component. However, FIR fine structure lines are relatively unaffected by extinction, so we can directly measure the physical state (composition, density, temperature) of the warm atomic gas component and indirectly infer some average properties of the molecular clouds.

We are conducting a survey of the FIR emission lines Si II (35 μm), O I (63 μm), C II (158 μm), and O III (52 and 88 μm) in infrared bright galaxies. The first three lines are important coolants of the atomic component of the ISM; the O III lines are important in the ionized component. We have compared the intensities and ratios of these lines with our theoretical models of photodissociation regions (PDRs) (Tielens and Hollenbach 1985a,b; Wolfire *et al.* 1989a,b), shocked gas (Hollenbach and McKee 1979, McKee *et al.* 1984), to determine the physical conditions in the nuclei of NGC 6946, IC 342, and Arp 299.

Table 1. Far Infrared Extragalactic Line Observations[a]

Galaxy	Type	FIR Flux[b]	Line Flux (10^{-19} W cm^{-2})				
		(10^{-16}W cm^{-2})	Si II (35 μm)	O I (63 μm)	C II (158 μm)	O III (52 μm)	O III (88 μm)
NGC 6946	Sc	3.3	**8**	**9.6**	7.5[c]	...	...
IC 342	Scd	4.4	**9.4**	**5.7**	36[d]	...	...
Arp 299	merger	4.9	**3.7**	**3.8**	8.5[c]	**8.2**	**3.6**

Notes: a) Our recent results (45″ beam) are in boldface, b) FIR is the 44-123 μm integrated IRAS flux, c) From Stacey 1988, private communication (60″ beam), d) From Crawford *et al.* 1985 (60″ beam).

II. OBSERVATIONS

These observations were made in June 1988 and March 1989 using the facility Cooled Grating Spectrometer on the 91.4 cm telescope of the Kuiper Airborne Observatory. The effective beamsize was 45″ (HPBW) and the velocity resolution ranged between 95 km s^{-1} and 120 km s^{-1}. Calibration and water vapor absorption corrections for each fine structure transition were accomplished through observations of K3-50A and Orion-KL. Total integration time per line was $\sim$ 50 minutes. Table 1 shows the measured line fluxes.

III. RESULTS

In these three galaxies, the dominant excitation source for the FIR emission lines is identified as radiatively heated H II regions and PDRs (*i.e.*, star formation regions). We are able to distinguish this form of excitation from other forms by the measurement of the FIR line and continuum ratios: (C II/O I)$\simeq 0.1-1.0$ and (C II+O I+Si II)/(FIR Flux)~ 0.01. These ratios are indicative of PDR emission, rather than excitation by AGN's or shocks. More quantitatively, the modeling procedures outlined in Wolfire *et al.* (1989a,b) can be applied to derive physical parameters for these galaxies. The models provide estimates of the ambient FUV radiation field and the density of the atomic gas from the flux ratios. These derived quantities, along with CO molecular mass estimates from the literature, and the individual line fluxes from Table 1, allow us to construct models of the ISM in these galactic nuclei, models which include the warm atomic gas component (the PDRs). Our results for these three galaxies are summarized in Table 2.

Table 2. Derived Astrophysical Quantities

Galaxy	n (cm^{-3})	T_a (K)	G_0 (ISRF)	M_a (10^7 $M_\odot$)	M_m (10^7 $M_\odot$)	ϕ_A	ϕ_V	N	r_{cl} (pc)	n_e (cm^{-3})
NGC 6946	10^4	200	10^3	1	100	0.1	3×10^{-5}	10^6	1.0	...
IC 342	10^4	100	10^2	2	5	2	10^{-4}	10^8	0.1	...
Arp 299	3×10^3	200	10^3	60	100	0.1	10^{-6}	6×10^8	0.2	600

Notes: Global parameters for gas clouds in the 45″ beam: n is the gas density, T_a is the temperature of the warm atomic component, G_0 is the incident FUV flux in units of the average interstellar radiation field (ISRF), M_a is the mass of the warm atomic gas, M_m is the molecular mass from CO observations, ϕ_a is the area filling factor of the warm atomic component, ϕ_V is the volume filling factor of neutral cloud material (molecular and atomic), N is the number of clouds, r_{cl} is the radius of a typical cloud, and n_e is the H II region electron density.

For IC 342 and Arp 299, the warm (T$\sim$100–200 K) atomic gas mass is comparable to the molecular mass and the fundamental "cloud building block" is a clump of radius 0.1–0.2 pc and mass $\sim$ 1 $M_\odot$. Each clump is exposed to an average interstellar FUV flux of $\simeq 10^2-10^3$ times the ISRF. However, in NGC 6946, the fundamental unit is a cloud of radius 1 pc and a mass 10^3 $M_\odot$, consistent with a more quiescent, less FIR bright central region than is seen in IC 342 and Arp 299.

An unexpected result of our study is that the Si II lines detected in each of these galaxies display Si II/C II and Si II/O I ratios ($\sim$1), which are comparable to those in M82. The relative Si II emission in all these galaxies is strong; comparable ratios in our galaxy are found only in high density, high FUV regions, such as M17 and the Galactic center.

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